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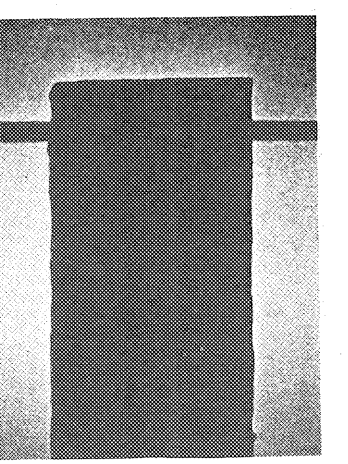
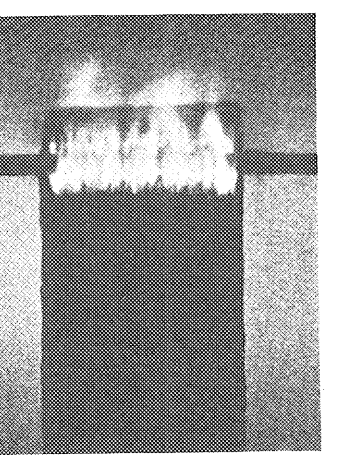
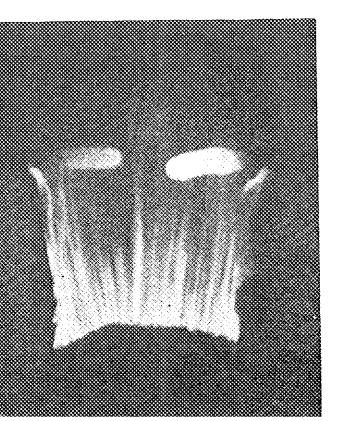
Combustion Chemistry Links Past with Future 74

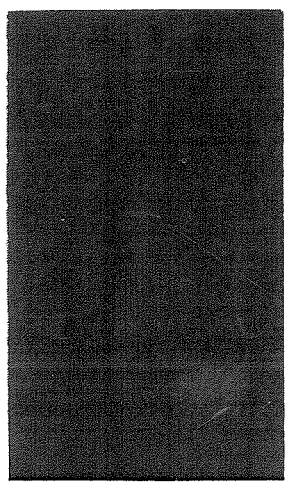






THE COVER: Atlantic Research scientist uses high-speed photography to study burning of solid propellant strand

COMBUSTION and Propulsion Research



That venerable branch of chemical science, combustion chemistry, links the past with the future in its application to space age developments. It also links chemists with physicists, engineers, and other members of the various professions in a unified effort to reach the planets.

DR. S. S. PENNER, California Institute of Technology, Pasadena, Calif.

Combustion chemistry is one of the oldest branches of chemical science. Among its pioneers must be counted Lavoisier, Bunsen, and others whose names belong among those of the founders of chemical science. That this close connection between combustion science and chemistry continues is well illustrated by the work of C. N. Hinshelwood and N. N. Semenov in elucidating chain reaction mechanisms, for which they shared the 1956 Nobel Prize. This work was at least partly motivated by difficulties in solving a classical problem in combustion science, viz., measurement of explosion limits for premixed gases in closed vessels.

Historically, the beginnings of combustion science are inextricably linked with research in chemical kinetics and high temperature thermochemistry. Fairly recently, a new impetus to progress in the field resulted from a broadened scope: Combustion became essentially a study of chemical reactions in flow systems, thus leading to a combination of the disciplines of fluid dynamics and chemical kinetics. This particular combination is not new. In various specialized forms, it has long been familiar to chemical engineers. But an important period of accelerated growth and deepened understanding came from the stimulus of modern propulsion development, particularly from the evolution of rockets and ramjet engines. Only 20 years ago, combustion science in the western nations was largely a specialized study of chemical reaction mechanisms and rates, practiced by a small group of physical chemists. As such, it was sparked by the pioneering efforts of men like Bernard Lewis, Hoyt C. Hottel, Wilhelm Jost, and Sir Alfred Egerton.

The significance of the interplay between fluid mechanics and chemical kinetics was first recognized, perhaps, by the Russian school of Semenov, Zeldovich, Frank-Kamenetsky, and others, whose research activities remained relatively unknown in the West until the early 1950's. During the past decade, the beginnings of a well-defined scientific discipline have evolved, encompassing in quantitative form the classical fields of chemical kinetics, thermochemistry, and fluid mechanics. This discipline lends itself to rigorous formulation of some interesting problems. But, at the same time, it demands of its adherents a very highly developed intuition and

physical insight in order to permit the reduction of physical problems to tractable form. In general, the largest uncertainties in quantitative work are still directly related to deficiencies in our knowledge of chemical reaction rates and mechanisms.

Basic Combustion Research

We may conveniently discuss the efforts to understand the atomic and molecular processes responsible for observable combustion phenomena by considering a simple experiment. Thus, we may look at the essential aspects of the physical phenomena that occur upon ignition—with a match, for example—of a combustible mixture of gases that are contained in a long tube.

In this experiment, the astute observer will ask at least five separate questions:

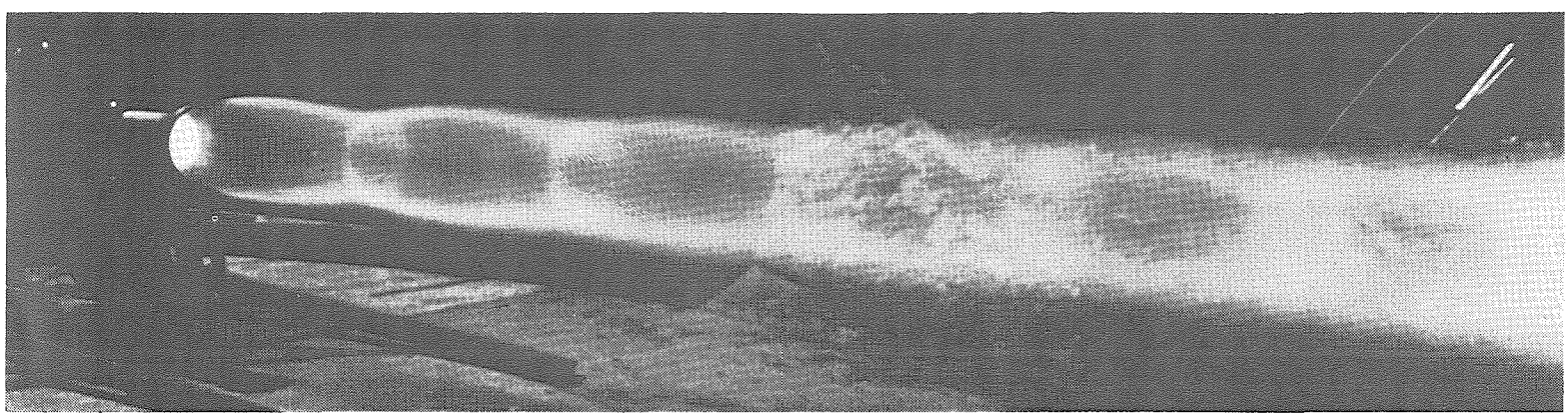
- What conditions are required for igniting a combustible mixture?
- After ignition, why does a stable flame sometimes fail to propagate through the gas mixture; that is, what is it that determines flammability limits?
- If a stable flame (deflagration wave) does propagate through the gas mixture, what is the propagation velocity—what determines the laminar flame, or deflagration, velocity?
- Why does the propagation velocity appear to accelerate in sufficiently long tubes, particularly if the tube wall is roughened? In other words, what determines the transition from deflagration to detonation?
- Again, for a sufficiently long tube, the propagation velocity reaches a steady high value; that is, a steady detonation wave propagates through the tube. What is it that determines the propagation velocity of a detonation wave?

If we look at these questions sequentially, we see that the first, second, and fourth are related to transient phenomena, while the third and fifth, on the other hand, are concerned with the magnitude of observed, stable propagation velocities.

Laminar Flames in Premixed Gases

A truly basic problem of combustion science is to describe laminar flame propagation in a quantitative way. The treatment requires a detailed description of the interplay of chemical and physical processes in a flow system, and this, in turn, can be had only by solving the coupled equations of flow with chemical reactions.

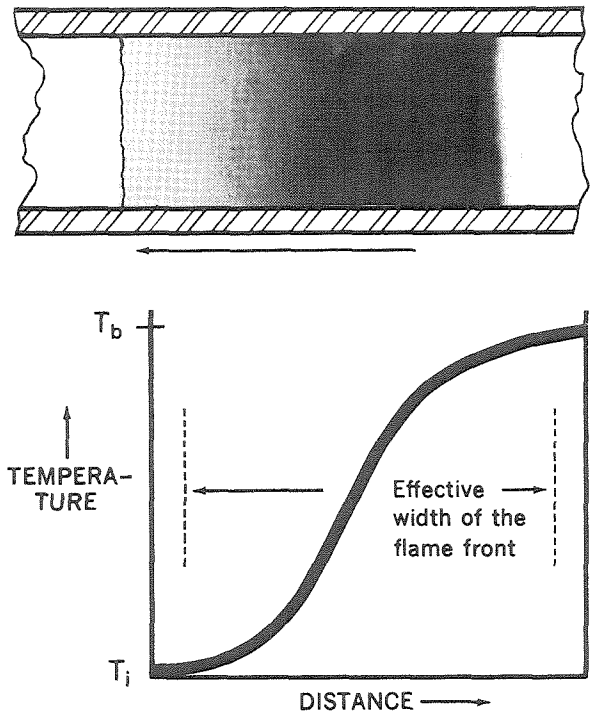
Static Test. *Stability of the shock diamonds in the exhaust pattern of medium size solid-propellant rocket engine indicates stable and reproducible combustion. The mechanism of decomposition and burning rate of solid propellants is important in understanding stability behavior in solid-fuel rockets*



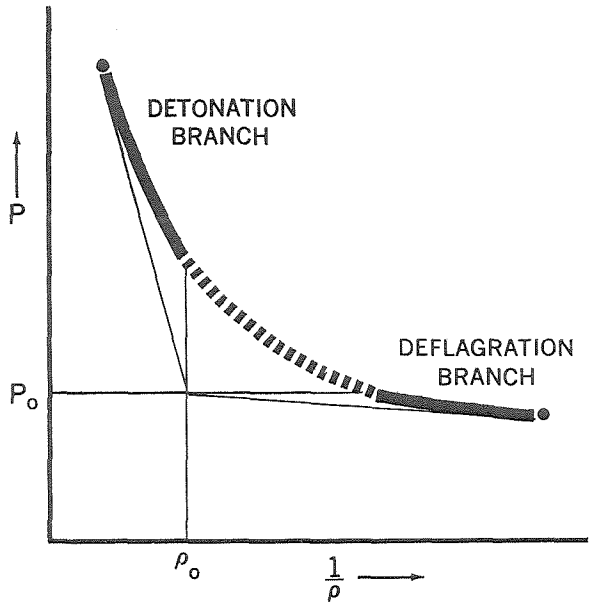
The ideal process of one-dimensional, laminar flame propagation without convection currents, heat losses, or other wall effects can be visualized in a perfectly smooth-walled tube containing a quiescent and combustible mixture of gases. The one-dimensional flame front lies normal to the axis of the tube, and it moves through the gas mixture in a direction parallel to the axis. The flame velocity (or laminar burning or deflagration velocity) is taken as the propagation velocity of the flame region into the unburned gas mixture.

The laminar flame velocity is an eigenvalue of the problem. It depends on gas composition, temperature, and pressure through the parameters measuring the "over-all" chemical reaction rate for conversion of reactants to reaction products; and it depends, at the same time, on applicable heat conduction and diffusion rates, as well as on such other physical quantities as the heats of reaction and the specific heats.

The adiabatic, one-dimensional problem has a solution only if we assume either that the chemical reaction rates are zero below a well-defined ignition temperature, or that a small amount of heat is lost at a region where the flame is anchored—that is, at the flame holder. Theodore von Kármán, first recipient of the National Medal of Science (and with whom the author was associated on combustion research some 10 years ago), J. O. Hirschfelder, and other scientists have demonstrated the mathematical equivalence of these two concepts, and predicted flame velocities have been shown to be in good accord with measured values in the cases of those gas mixtures where good reaction rate data are available. Examples of such agreement are found in the ozone decomposition flame in ozone-oxygen mixtures, in flame propagation through hydrogen-bromine mixtures, and in the hydrazine decomposi-



One-Dimensional Flame Propagation. *A one-dimensional, laminar flame, propagating without convection currents, heat losses, or other wall effects, represents an idealized process which illustrates the essential features of the physical phenomena. A very small pressure drop takes place across the flame front, accompanied by a large temperature rise. The curve in the lower portion of the illustration (not aligned with the schematic diagram) represents the temperature rise across a laminar flame "front." The temperature, T_b, is approached asymptotically, and the width of the flame front is therefore not strictly defined. The adiabatic, one-dimensional problem of flame propagation has a solution only if it is assumed that the chemical reaction rates are zero below a well-defined ignition temperature, or that a small amount of heat is lost at a region where the flame is anchored (that is, at the flame holder). The mathematical problem can be described quantitatively by solving the coupled equations of flow with chemical reactions.*



Rankine-Hugoniot Curve. *The Rankine-Hugoniot curve is a plot of pressure vs. specific volume and may be constructed for any given real gas mixture by solving the applicable set of equations for conservation of energy, mass, and momentum. The initial state of the gas before the advancing reaction front is represented by the point $(p_0,1/\rho_0)$. The calculated final states lie along the Rankine-Hugoniot curve. The velocity of a stable detonation wave corresponds closely to the final state represented by the point of tangency along the upper Hugoniot curve for a line drawn from $(p_0,1/\rho_0)$. The upper solid branch of the curve is formed by end states corresponding to detonation waves which advance at a velocity greater than the velocity of sound into the unreacted gas mixture. The lower solid branch corresponds to deflagration waves with propagation velocity less than that of sound. The broken line represents unobservable end states. The points of tangency are termed the upper and lower Chapman-Jouguet (C-J) points, respectively, with the lower C-J point corresponding to an unobservable limiting state.*

tion flame. It has been found useful, in solving some laminar flame problems, to introduce an approximation which is analogous to the steady-state approximation of classical chemical kinetics.

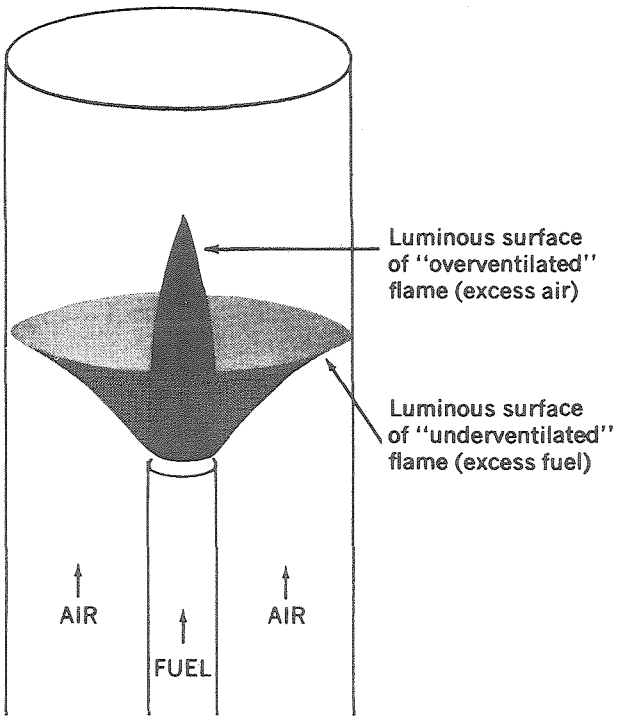
Searching experiments have been done on flame structure with spectroscopic and other techniques. At atmospheric pressure, such experiments provide information about the temperature and composition profiles in a spatial region having a thickness which is of the order of a hundredth of a millimeter. This "thickness" of the flame can be increased by burning the gaseous mixture at reduced pressure.

A finding of particular interest to chemical scientists is that the emission spectra that are characteristic of regions of rapid reaction are usually dominated by excited free radicals which radiate intensely. Several scientists, K. E. Shuler and A. G. Gaydon among them, have concluded that the emitters may have vibrational and rotational energy distributions that are essentially unrelated to the local mean energies.

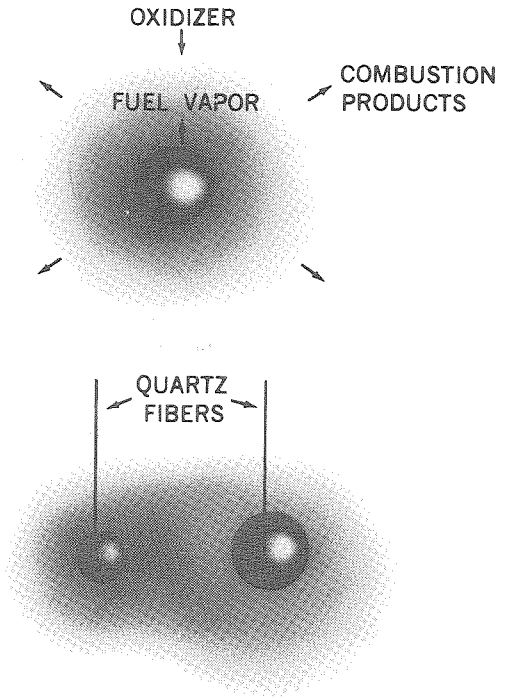
Detonation Waves in Premixed Gases

I should like to deal next with the fourth and fifth of the questions that I enumerated earlier. In any real experiment, and for a tube that is sufficiently long, the reaction "front" described in the one-dimensional tube will first become distorted, and then it will accelerate until, ultimately, a stable detonation wave is propagated at constant velocity.

This velocity can be calculated, in good approximation, if we assume that the state of the gases behind the detonation front corresponds to the upper Chapman-Jouguet point of the Rankine-Hugoniot curve. The Rankine-Hugoniot curve is described separately on this page, but, briefly, it is a plot of pressure *vs.* specific volume and is constructed for a given gas mixture by solving the applicable set of equations



Diffusion Flames. *Flames in gases that have not been premixed are referred to as diffusion flames. S. P. Burke and T. E. W. Schumann made the classical contribution in this field in 1928, when they assumed that the flame boundaries in initially unmixed gases are located at the region where the delivery rates by diffusion of fuel and oxidizer occur in stoichiometric proportions. Burke and Schumann's concept is illustrated for flow in two concentric tubes with air and fuel moving with equal linear velocities. When the relative diameters of the tubes are such that an excess of air is delivered, the resulting flame is overventilated and the luminous surface of the flame converges toward the tube axis as the reactants proceed downstream. On the other hand, when excess fuel is delivered, an underventilated flame results and the luminous surface moves outward, forming a cup, the rim of which touches the wall. These two cases are both shown in the sketch. Since the flame reactions are extremely rapid, the flame front is, in a first approximation, infinitesimally thin.*



Combustion of Liquid Fuel Droplets. *The burning of liquid fuel sprays is a subject for combustion studies having considerable practical importance. The burning of an individual droplet in a freely falling chamber permits a study of the characteristics of a spherically symmetric, heterogeneous diffusion flame. For a droplet in free fall, the influence of natural convection is eliminated. The mathematical problem is an eigenvalue problem which yields the consumption rate of the fuel droplet as a function of the parameters that define the physical situation. Calculated and observed burning rates are generally in fair accord; for example, the dependence of burning rate on oxygen concentration is predicted quite accurately. The burning rate of the droplet is described quantitatively by the rate of change of the square of the droplet diameter with time. This rate of change becomes constant after a relatively short induction period, even in those cases where two or more droplets are burning in close proximity.*

for the conservation of energy, momentum, and mass.

Many experiments have been used to demonstrate that stable detonation waves propagate at velocities very close to those corresponding to the end state (point of tangency) predicted on the upper branch of the curve. It has never been proved rigorously, however, that this predicted point does, in fact, represent the only allowed end state for the set of interdependent (chain) reactions occurring in detonations in all real gas mixtures.

We consider now another aspect of detonation research. Recent theoretical studies and experimental research have been concerned primarily with elucidating the microscopic structure of the very thin detonation front. J. G. Kirkwood, J. O. Hirschfelder, and their collaborators have been particularly active in the theoretical work, while G. B. Kistiakowski and others have been deeply engaged in the experimental investigations.

The starting point for the theoretical studies lies in the Zeldovich–von Neumann–Döring suggestion that a detonation wave consists of a shock wave, behind which the chemical reactions go to completion. The front of the shock wave, often called the "von Neumann spike," produces very rapid increases in pressure, density, and temperature; but the severity of the "jumps" in these parameters is decreased, if proper allowance is made for viscous dissipation, heat conduction, and diffusion. The pressure and density decrease as the chemical reactions proceed, with pressure falling ultimately to about one half of its initial value. Various theoretical difficulties are associated with our present understanding of the structure of the tail end of a detonation wave.

Among the interesting detonation studies is the following: the work of W. A. Bone, R. P. Fraser, and W. H. Wheeler in England on spinning detonations, a phenomenon that might prove intriguing even to the nonspecialist, who might enjoy visualizing its

travel through the gas mixture in a long tube. We know that spinning detonations tend to occur in gas mixtures near the limits of detonability and that they are characterized by periodic velocity changes.

The mechanism of transition from deflagration to detonation has been investigated particularly by Y. B. Zeldovich in the U.S.S.R. and by A. K. Oppenheim in the U.S.; the study of two-dimensional effects in the propagation of detonation waves has been pioneered by J. A. Fay of the Massachusetts Institute of Technology.

Flammability and Quenching Limits

In burning gaseous mixtures, we find experimentally that there are composition limits for all chemical mixtures, outside of which it is impossible to sustain either laminar flames or detonation waves. These limits are called "limits of flammability" or "limits of detonability," as the case may be. Similarly, a given gas mixture will cease to burn above a burner port when the port diameter is made sufficiently small; these limits are called "quenching limits." Limit phenomena are also observed in other combustion processes. For example, a solid propellant grain, such as a stick of ammonium perchlorate, will cease to burn below a well-defined pressure—that is, below the "low pressure deflagration limit."

We now believe that these limit phenomena are always associated with energy losses from the system. Flammability limits in tubes of arbitrarily large diameters are imposed by radiative energy losses. Quenching limits are determined by energy losses to the burner port. Low pressure deflagration limits of solid ammonium perchlorate are probably imposed by an effective removal of energy from the gas-phase combustion region through a change in the gasification mechanism of the propellant surface below a well-defined pressure.

The idea that limit phenomena are associated with energy loss from the system was prevalent in the Russian literature about 20 years ago. Since then, it has been transcribed to the western literature in more quantitative form by E. Mayer of the U.S. and D. B. Spalding of England.

Diffusion Flames

Thus far we have discussed only flame processes in premixed systems. But flame propagation in initially unmixed reactant systems is of equal fundamental importance and, moreover, is of far greater technical importance.

S. P. Burke and T. E. W. Schumann made the classical contribution in this field in 1928, when they proposed the idea that the flame boundaries for initially unmixed gases are located at the spatial regions where the rates of delivery by diffusion of fuel and oxidizer occur in stoichiometric proportions. In first approximation, the flame front is then infinitesimally thin.

Even though the analytical transcription of the Burke-Schumann hypothesis involves many additional approximations, the calculated and measured flame shapes are in good agreement. So are the calculated and measured composition profiles. A. G. Gaydon of London's Imperial College of Science and Technology and H. G. Wolfhard, now associated with Thiokol Chemical, studied the detailed structure of the diffusion flame spectroscopically in a two-dimensional geometry, and they found that it shows the expected gross agreement and deviations in detail from the idealized diffusion flame model.

An interesting, spherically symmetric, heterogeneous (that is, two-phase) diffusion flame can be realized without troublesome convection effects by burning a fuel droplet in an oxidizing atmosphere in a free-fall chamber, as was done by Seiichiro Kumagai at the University of Tokyo. The treatment of this phenomenon involves an eigenvalue problem which yields the consumption rate of the fuel droplet as a function of the physicochemical parameters defining the problem. Calculated and observed burning rates generally are in fair accord and, furthermore, the dependence of the burning rate on oxygen concentration is predicted quite accurately.

Customarily, we describe the burning rate of the fuel droplet by means of the evaporation constant K′, which is defined as $-\frac{dD_l^2}{dt}$ where D_l is the liquid droplet diameter at time t. Interestingly, $-\frac{dD_l^2}{dt}$ becomes constant after a relatively short induction period, even for two or more droplets burning in close proximity. In the latter case, however, we are unable to calculate an accurate absolute value of K′.

The mechanism of flame propagation in a one-dimensional array has been studied by using a schlieren optical system. The results are consistent with the idea that a droplet adjacent to a burning droplet bursts into flame at that time when a fixed minimum energy has been fed into the droplet, mostly by conductive heat transfer.

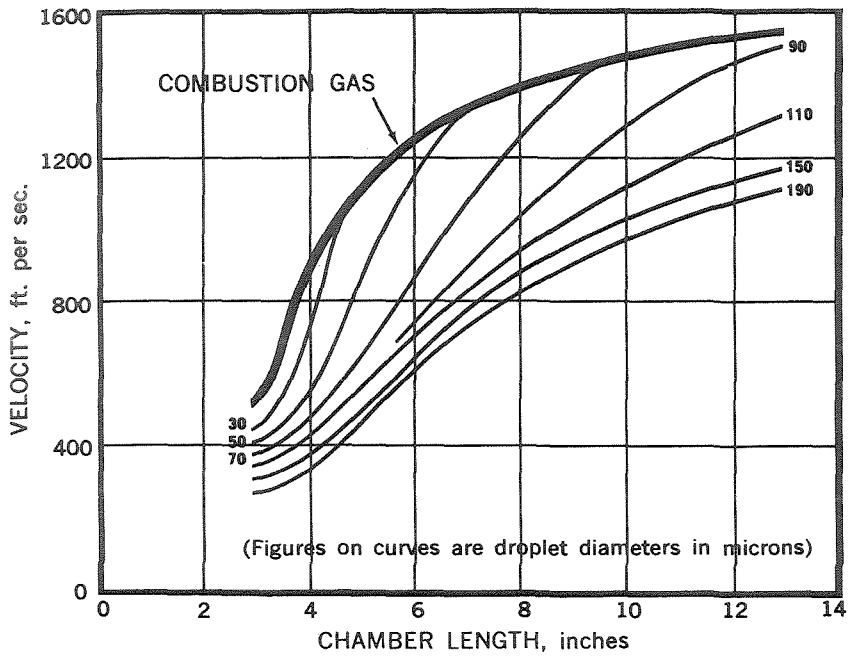
Propulsion Development

Combustion research is one of those areas of science where, even though much fundamental work remains to be done, basic concepts are quite rapidly put to use in research directed toward solution of problems of potential practical importance. Engine development provides some interesting examples:

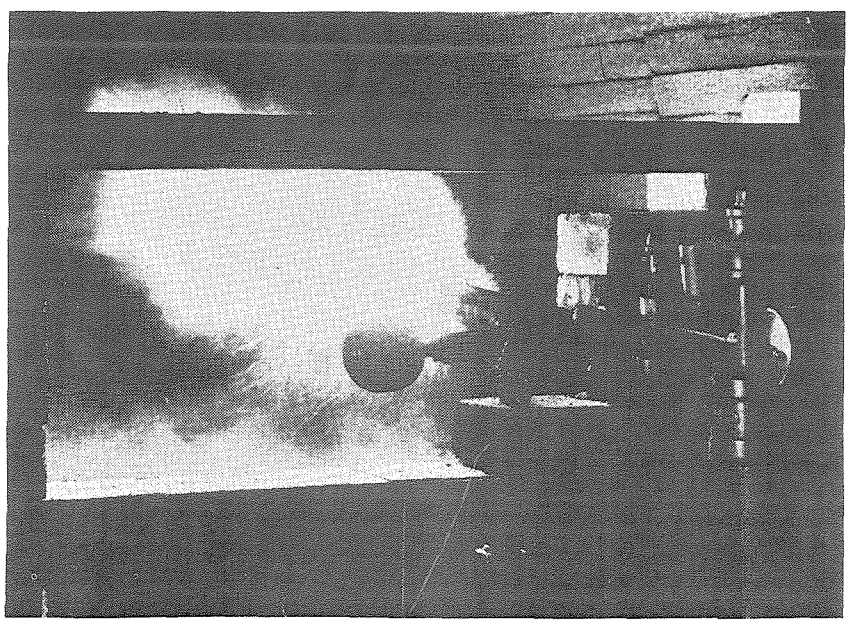
- Supersonic burning in hydrogen-air mixtures, which is a key problem in the development of the hypersonic ramjet engine.
- Spray burning, which is the essential problem in understanding the combustion mechanism in liquid fuel rocket engines.
- The mechanism of decomposition and burning rate of solid propellants, which is an important problem in designing solid-propellant materials from first principles and in understanding the stability behavior of solid rockets.
- Chemical changes during subsonic and supersonic flow in nozzles. Such

Suggested Additional Reading

1. Gaydon, A. G., Wolfhard, H. G., "Flames, Their Structure, Radiation, and Temperature," 2nd ed., London, Chapman and Hall, Ltd., 1960.
2. Lewis, B., von Elbe, G., "Combustion, Flames and Explosions of Gases," 3rd ed., New York, Academic Press, 1961.
3. Penner, S. S., "Chemistry Problems in Jet Propulsion," London, Pergamon Press, Ltd., 1957.
4. Proceedings of the AGARD Combustion and Propulsion Panel.
5. Proceedings of the International Combustion Symposia.
6. Spalding, D. B., "Some Fundamentals of Combustion," New York, Academic Press, 1955.



Spray Droplet Velocities. *The operating characteristics of liquid-fuel rocket engines are strongly affected by fuel droplet size, droplet size distribution, and droplet velocity through the combustion chamber. R. S. Levine, S. Lambiris, and L. B. Combs have used streak photographs to estimate droplet velocities in the combustion chamber of a transparent, two-dimensional, liquid-fuel rocket engine, and they have used the resulting data in a one-dimensional theory to construct velocity vs. distance profiles for droplets having various initial diameters. The heavy upper line represents the velocity of the combustion gas, while the other lines represent the velocities of droplets having the initial diameters shown for each line. The droplet size decreases during burning; as the droplets become very small, they begin to approach the velocity of the gas asymptotically.*



Intriguing Problems. *A statistical theory of spray burning of liquid fuel may be constructed, but full utilization cannot be realized because all the required parameters are not available. We need more information, for example, on what happens upon collision between droplets, as well as on other factors. Here, a test is made of fuel burning with oxygen-enriched air*

changes have potential implications for the chemical process industries, and they play a significant role in the precise theoretical evaluation of the performance of chemical rocket engines. They may well determine the ultimate utility of the nuclear-powered solid-core rocket and the ramjet engine that uses hydrogen as the driving fluid; and they may also enter, in a decisive manner, in the development and construction of high-Mach number air-breathing engines.

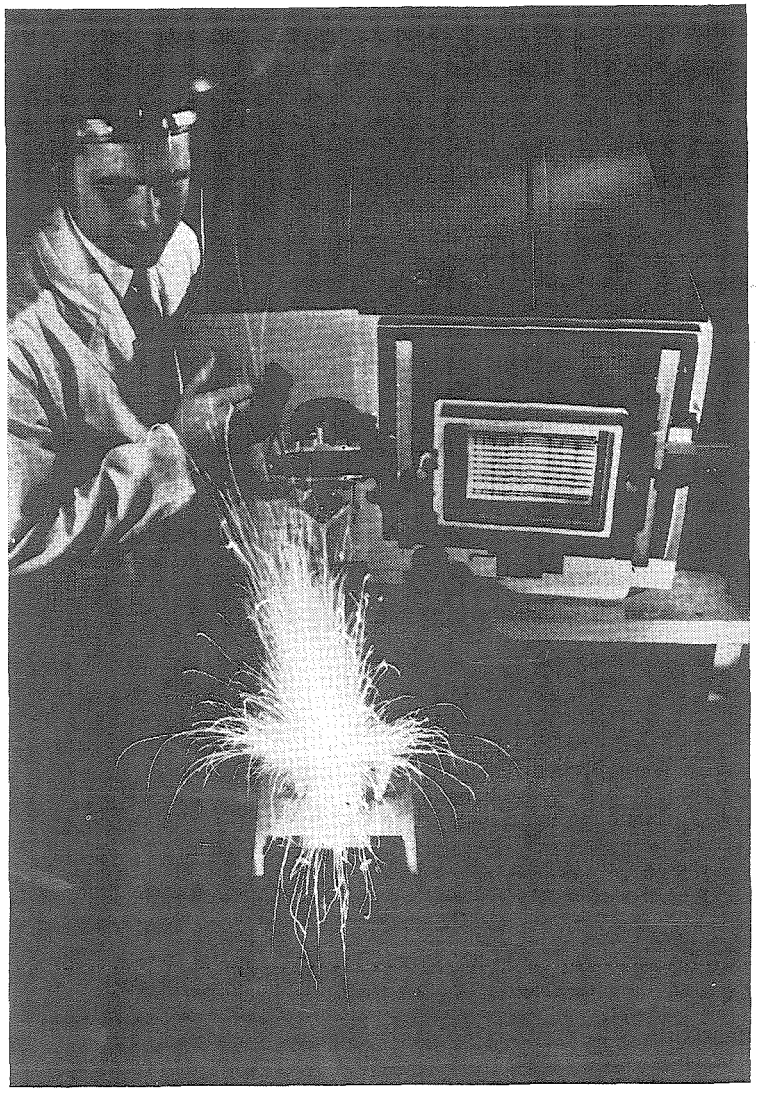
I shall now consider some of these interesting studies in greater detail.

Supersonic Burning

Recent studies of the hypersonic ramjet—an air-breathing engine that has been flown extensively at flight speeds up to about 4000 feet per second—indicate that optimum results can be achieved at very high flight speeds only if it is possible to burn vaporized fuel in a high velocity air stream. By "very high flight speeds" I refer to Mach numbers greater than about 10 or flight velocities greater than about 10,000 feet per second. (Mach number is defined here as the ratio of the flow velocity to the speed of sound in normal air.) The vaporized fuel referred to is hydrogen or kerosine injected at velocities somewhat above 1000 feet per second into an air stream with velocities ranging from about 2000 to about 8000 feet per second. This type of problem has been studied by fluid dynamicists such as Antonio Ferri, P. A. Libby, M. A. Bloom, and others.

The preferred arrangement is similar to that shown for a diffusion flame on page 77, except for the higher and dissimilar flow velocities, the removal of the outer bounding cylinder, and an arrangement of many parallel, burning fuel jets. The success of this program depends crucially on the attainable reaction rates in hot gas mixtures and also on the mixing rates between the reactant streams, which are now determined by turbulent transport processes.

Clearly, if the mixing processes or the ignition and reaction rates are too slow, then an enormously long combustion chamber will be required in view of the very high velocities of the reactant streams. Quantitative kinetic studies have been made recently by N. N. Semenov, J. A. L. Nicholls, R. E. Duff, S. H. Bauer, and others. Fortunately, these studies suggest that, at



Composite Propellant. *Many scientists are engaged in experimental studies on composite solid propellants. Dr. L. A. Povinelli, NASA Lewis Research Center, gathers spectrograms of burning solid propellant composed of ammonium perchlorate, polybutadiene acrylic acid, and 9% dispersed aluminum. With better understanding of the combustion mechanism as the immediate goal, the work is aimed ultimately at learning what dispersed aluminum does to specific impulse and stability*

about 1500° K. and atmospheric pressure, the ignition times are of the order of a few microseconds and the reaction times are of the order of tens of microseconds. Furthermore, the mixing times for representative inlet conditions are of the order of tens to thousands of microseconds. Hence, reasonable combustor lengths appear feasible for the hydrogen-air reaction in supersonic burning, provided the mixing lengths for the gases can be made sufficiently short. The latter condition appears to have been met recently in work performed by Antonio Ferri and his colleagues at the Polytechnic Institute of Brooklyn.

Spray Burning

We may construct a statistical theory of spray burning, as F. A. Williams has done, by starting from an equation which is analogous to the Boltzmann equation. Unfortunately, the parameters needed for fully utilizing the statistical theory of spray burning are not available. We do not understand quantitatively the physical processes occurring upon collision between droplets, for example. Nor do we understand the influence of evaporation on droplet drag, the chemical and transport rates in arrays of burning droplets, and other factors that must be considered. Fairly successful one-dimensional theories of spray burning have been constructed, however, for correlating observed droplet velocity profiles in liquid-fuel rocket engines.

R. S. Levine, S. Lambiris, and L. P. Combs have estimated droplet velocities in the combustion chamber of a transparent, two-dimensional liquid-fuel rocket engine by using streak photographs. These have been used in a one-dimensional theory to construct velocity *vs.* distance profiles for droplets with various initial diameters.

Burning Mechanism of Solid Propellants

During the World War II years, Farrington Daniels, B. L. Crawford, Jr., and O. K. Rice studied extensively the burning mechanism of double-base solid propellants, for example, homogeneous propellants containing nitrocellulose and nitroglycerine. More recently, attention has been focused on heterogeneous composite solid propellants and on the separate components from which these propellants are prepared. In particular, Raymond Friedman of Atlantic Research has done some thorough experimental work on pure ammonium perchlorate, and William Nachbar and his colleagues at Lockheed have done equally thorough theoretical work on the same substance. In addition, R. D. Schultz and his colleagues at Aerojet-General have conducted similar studies on various hydrocarbon-containing binders. As the result of these studies, a beginning has been made in understanding the mechanism of decomposition of the pure components.

Martin Summerfield and his colleagues, as well as other scientists, have performed detailed experimental studies on the composite propellants themselves in order to answer such basic questions as the influence of particle size on burning rate. When coupled with heuristic arguments concerning burning mechanisms and rates of the propellants, the results of these experimental studies lead to formulas that are useful for correlating the measured dependence of burning rate on pressure for various powder compositions. Unfortunately, the time appears to be far in the future when

knowledge of the chemical composition alone will be enough for an absolute prediction of burning rate. But the implications of solid propellant burning rate for the stability behavior of rocket motors is an area that has recently received very serious study by several scientists, F. T. McClure of Applied Physics Laboratory among them.

Chemical Changes During Nozzle Flow

About 15 years ago, quantitative analytical studies of chemical reactions during flow in de Laval nozzles were carried out by the author in order to define the precise theoretical performance limits of chemical rocket engines. It is apparent that recombination reactions in the nozzle, involving atoms and free radicals that were formed in the combustion chamber, are generally exothermic and will increase the temperature and translational energy of the gases. Hence, they will lead to improved thrust or performance by the engine. The relative rates of the chemical reactions and of the flow in the nozzle determine the extent to which chemical changes occur. Using these ideas, it is not difficult to develop simple analytical criteria that permit the classification of many chemical systems into those involving no chemical changes during the residence time and those where chemical equilibrium is essentially maintained.

In recent years, informative experiments with the $N_2O_4 \rightleftharpoons 2NO_2$ system by P. P. Wegener and elaborate analytical work by J. G. Hall and his associates have been performed for nozzle flow of heated air discharging from hypersonic tunnels, and P. A. Libby has done similar work for the combustion products formed in hydrogen-oxygen systems. The theoretical studies are of dominant importance in defining the performance of hypersonic ramjets. They are also interesting in connection with the development of rockets using high-energy propellants.

For optimum performance, the nuclear rocket that uses hydrogen as the driving fluid must be developed in such a way that extensive recombination of hydrogen atoms occurs in the nozzle. Possibly, this objective can be achieved by replacing the homogeneous three-body (gas phase) recombination reactions with two successive two-body processes, through the judicious introduction of finely divided solid materials.

Trends for the Future

Among the important areas of combustion research that we have not considered here are the perennial problems concerning fuel utilization in internal combustion engines and burners. But these topics properly form the subject of another survey, which would overlap the present discussion only insofar as some of the pertinent basic studies on flame propagation are concerned.

In commenting on the future of combustion science, the next important step motivated by propulsion development seems evident. With the advent of higher flight speeds during cruise and entry into planetary atmospheres, temperature levels will rise to the point where radiative transfer processes and photochemical phenomena, considered negligible at lower temperatures, will become important and perhaps even dominant. Theoretical and experimental combustion studies should therefore increasingly encompass, first, radiative energy transfer and, ultimately, photochemical reactions and other elementary processes involving the interplay of photons with elementary reaction steps. Coupled with this development must be the design and construction of cooled or ablating materials, probably plastics, as well as the systematic measurement of new sets of thermochemical data on materials designed for various high temperature applications.

One more interesting point: The demands of propulsion development have led to such detailed scrutiny of the complex reaction mechanisms and reaction rates of a number of basic chemical processes that major contributions to our understanding of the chemical kinetics of systems such as hydrogen-air have resulted. Another pertinent example of this lies in the highly successful description of reactions in heated air. The work on heated air was motivated largely by our need for a better understanding of heat transfer during missile and satellite re-entry into the atmosphere of the earth. Similar problems will, no doubt, soon be tackled relative to entry into the atmospheres of Mars, Venus, and other planets. The prospect of landing on Venus, for example, lends particular urgency to a study of reaction kinetics in mixtures of carbon dioxide and nitrogen.

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